

Southeast Asia Oceanography

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LONG-TERM GOALS

I am interested in better defining the magnitude and variations of the Pacific to Indian Ocean throughflow within the Indonesian Seas, which are considered to be key elements in the thermohaline balance of the Indian and Pacific Oceans, and perhaps to the global climate system. I also wish to improve our understanding of the source waters of the throughflow and of the mixing processes that alter the stratification enroute through the Indonesian Seas. These goals are met within the Arlindo Project, a joint oceanographic research endeavor of Indonesia and the United States.

OBJECTIVES

The specific objectives of the present phase of Arlindo research are to resolve the Indonesian throughflow velocity field and the mass, heat and freshwater fluxes across the central passages (Makassar and Lifamatola Passage) of the Indonesian Seas; to obtain a multi-year time series of the thermohaline stratification; to design and implement a strategy for throughflow monitoring to enable study of the oceanographic conditions within the Indonesian Seas and interocean exchange at time scales of ENSO cycles.

APPROACH

Deploy moorings in key throughflow passages to measure currents, internal waves, mean water column temperature and sea floor pressure variability. An array of CTD and tracer chemistry stations extend the time series begun in 1993.

Moorings: The current meters measure the mean and variable throughflow within the Makassar Strait and Lifamatola Passage. The flow in the upper 150 m is measured by upward-looking ADCPs; below that depth, the flow is measured by a series of Aanderaa RCM-8 current meters. IESs, which measure the mean temperature of the water column, were deployed in Makassar Strait. The mean temperature responds to internal thermocline oscillations and changes in water column heat content, which can then be related to circulation changes and internal tide activity. The deep pressure gauges accompanying the IES sensors (PIES) measure the changing pressure burden of the water column. Data collected from PIES may be used to relate variations in the along-axis pressure gradient flow in the Makassar Strait, which can then be correlated with the measured currents. Internal waves and tides are monitored by temperature measurements at the three mooring sites with temperature-pressure pods (self-contained temperature recorders, recording at 3.5 minute intervals). The t-pod data will greatly enhance the ability to resolve the internal wave activity and associated vertical mixing processes at the mooring sites. The study of satellite-based remote sensing (e.g., from TOPEX/POSEIDON, Advanced

Very High Resolution Radiometer, and Special Sensor for Microwave Imager) will provide regional views of sea surface temperature and sea level during the Arlindo Circulation period.

CTD array: The objectives of the Arlindo Circulation 1998 CTD array were to investigate interannual variability (in comparison with the 1993, 1994 and 1996 Arlindo CTD data) and to sample the region east of the Banda Sea, into the Aru Basin.

WORK COMPLETED

The most important returns of the 1998 field work were: 1. the recovery of current meter moorings in the Makassar Strait; 2. the recovery of three PIES in Makassar Strait; 3. a zonal section of CTD, LADCP and CFC stations along 5S in the Banda Sea, which ties together the various meridional views obtained on earlier cruises, with, for the first time, stations in the remote eastern Banda Sea.

The transport through Makassar Strait was measured as part of the Indonesian-USA Arlindo program, at two moorings deployed within the Labani Channel, a deep (2000 m) constriction (45 km) near 3S (Fig. 1). Both moorings were operative from December 1996 to February 1998, a 1.4 year time series, when the MAK-2 mooring was released and recovered. The MAK-1 mooring was recovered by grappling in early July providing a 1.7 year record. The recovery of MAK-1 was achieved with the support of the UNOCAL corporation. The MAK moorings were deployed during a weak La Niña phase. An El Niño condition began in March 1997, becoming extreme during 1997 summer and fall, relaxing in early 1998. Arlindo data will be the subject of much study by the Arlindo research team. The Lifamatola Passage (Fig. 1) mooring failed to release in the February 1998 attempt and will be recovered by grappling from the Baruna Jaya I in November 1998.

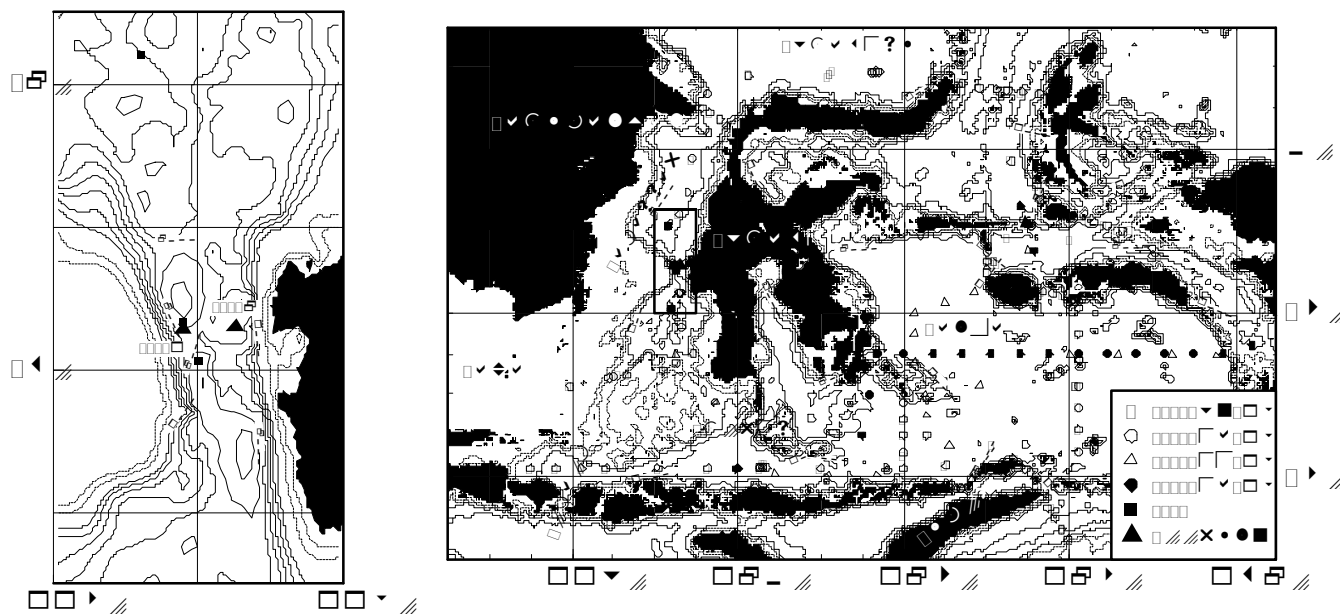


Figure 1. Distribution of CTD stations and time series moorings obtained by the Arlindo program. The position of the current meter and temperature-pressure pod moorings in Makassar Strait, MAK-1 ($2^{\circ} 52' S$, $118^{\circ} 27' E$) and MAK-2 ($2^{\circ} 51' S$; $118^{\circ} 38' E$) the subject of this note, are shown in the insert, as are the Pressure, Inverted Echo Sounder sensors (PIES).

RESULTS

The preliminary findings of the Arlindo Makassar MAK-1 and MAK-2 data are presented in Figs 2 and 3.

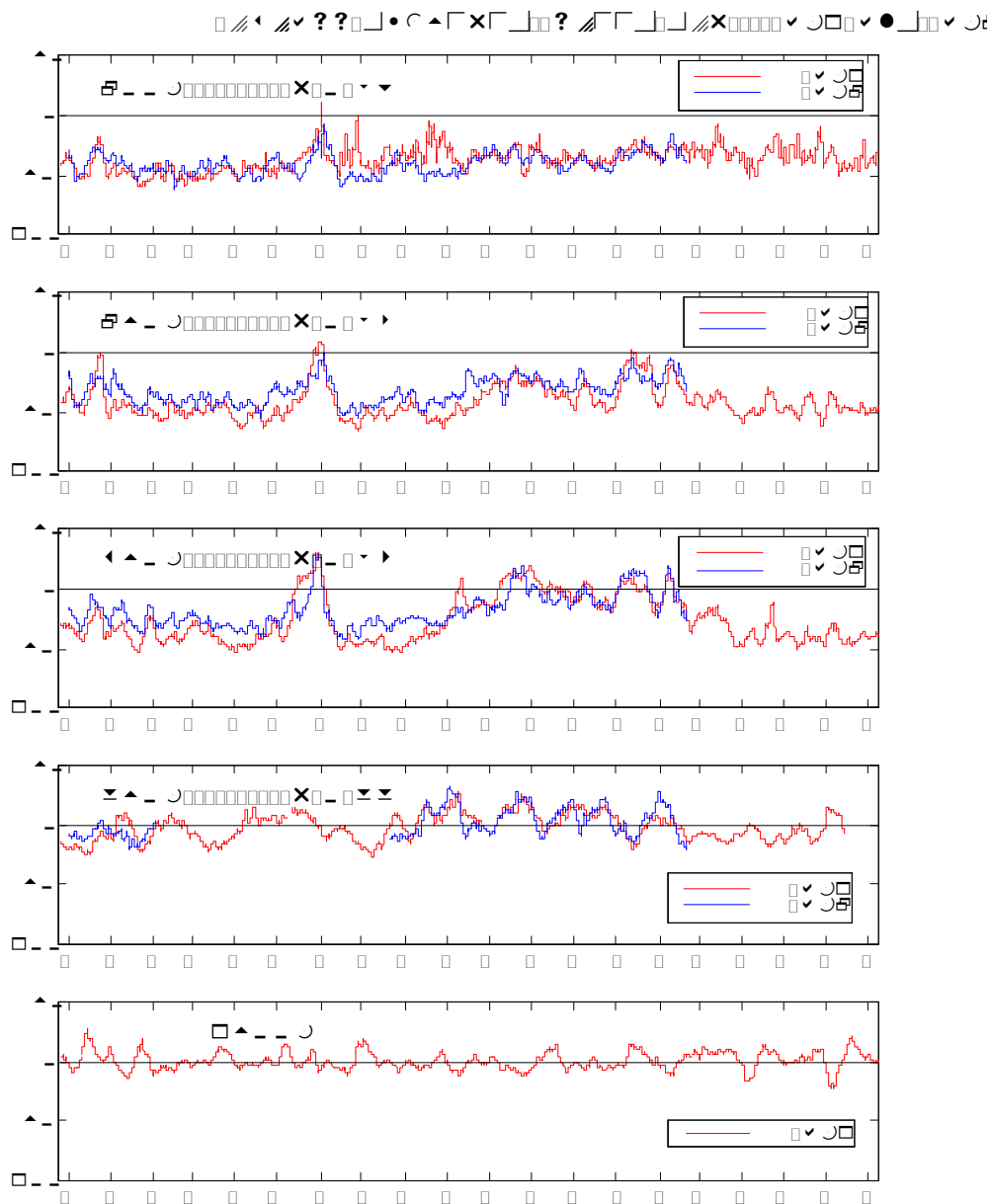


Fig. 2 The low pass (2 day) filtered along channel (orientation of 170°) speed recorded at each Aanderaa current meter of MAK-1 and MAK-2. Negative values denote flow towards the south, the direction of the interocean throughflow.

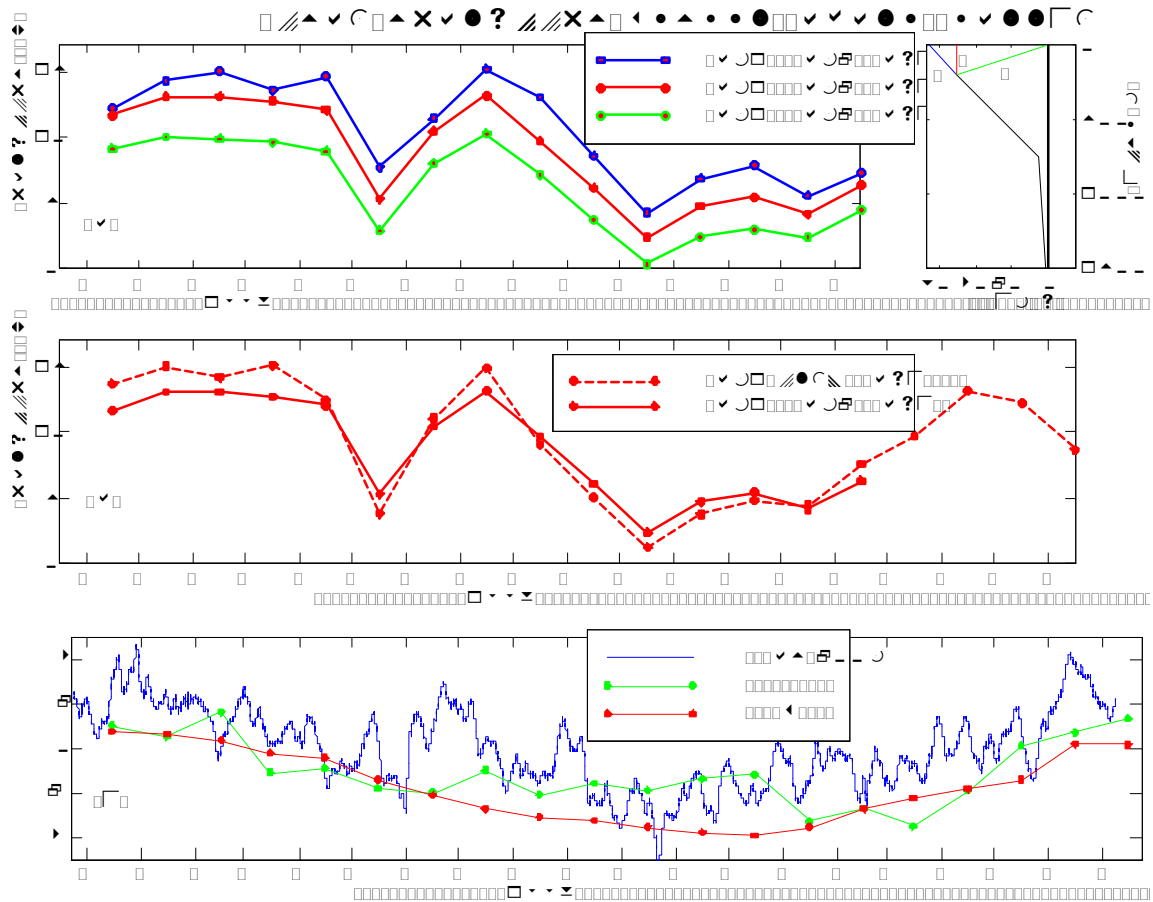


Fig. 3 Total southward or throughflow transport within Makassar Strait (displayed as positive values) for each month (Fig. 3a,b). As the data from the moored ADCP (deployed at 150 m) is still being processed (see text) we use three models for carrying the Aanderaa along channel speeds to the sea surface (insert adjacent to 3a). We favor Case B, which on average differs from A and C results by 2.4 Sv, about 25% difference. Transport determined from use of both moorings for the period up to February 1998, agrees closely with the use of only MAK-1 (3b), suggesting that one mooring may be sufficient in monitoring Makassar transport. The temperature recorded by the 200 m instrument of MAK-1 was processed to remove the mean vertical temperature gradient, recorded during the strong semi-diurnal blowover movements. An anomaly of temperature was then calculated, the difference between the temperature change expected from the mean temperature profile from that actually recorded. The temperature anomaly (Fig. 3c) compares favorably to the ENSO indicators of SOI and the SST anomaly at El Niño-3. The thermocline is deeper during La during El Niño.

There are several key points which will be explored in detail by the Arlindo team:

[A] The Makassar thermocline depth and transport reflect the phases of ENSO, with an ambiguous seasonal cycle: deeper thermocline, larger throughflow during La Niña; shallow thermocline, with reduced transport during El Niño. Additionally, during the El Niño months December 1997 to February 1998 the transport average is 5 Sv, while during the La Niña months of December 1996 to February 1997 the average is 12 Sv, a 2.5 fold difference.

[B] Along channel flow exhibits much activity at frequencies above seasonal. A special event occurs in May and June 1997 when a marked relaxation of the throughflow transport is recorded. Candidates for responsible processes are: Pacific Ocean Rossby waves, Indian Ocean coastal Kelvin waves, local atmosphere and dynamics internal to the Indonesian Seas.

[C] The Makassar Strait 1997 twelve month average throughflow is 9.3 Sv. This assumes that the flow above the shallowest Aanderaa equals the flow at that current meter (case B, Fig. 3). Other models for the surface flow yield 1997 transport average of 6.7 Sv (zero surface flow, case C, Fig. 3) to 11.3 Sv (thermocline shear is extrapolated to the sea surface, case A, Fig. 3). How to handle the water flow above the shallowest Aanderaa current meter is an important issue, not just for the mass transport but also for the interocean heat and freshwater flux and for monitoring array design. We will have a firmer idea of the surface layer flow when the moored ADCP data are processed. The MAK-2 ADCP has a record from 1 December 1996 to 9 March 1997 before it flooded; the MAK-1 ADCP data record will be processed later this year. The preliminary MAK-2 ADCP data show a maximum of along channel flow at 110 m, with near zero surface flow. The hull ADCP of the Baruna Jaya IV, the Indonesian research vessel used in the Nov/Dec 1996 deployment and Feb 1998 recovery of the MAK moorings reveal similar reduction of along channel speed in the surface layer. The MAK-1 monthly along channel speeds displays higher southward values at the 250 m instrument relative to the 200 m instrument for 13 of the 20 month record (the months with higher transport). The data suggests shear reversal between 200 and 250 m in the western Labani channel, closer to 100 m in the east.

[D] The Makassar transport (case B) determined from the Arlindo data is at the higher end of estimates derived from Timor Sea and Indian Ocean studies. While this would favor the case C throughflow of 6.7 Sv, with zero mean along channel flow at the sea surface this may not be the only explanation. Perhaps we are seeing a throughflow interannual (ENSO) signal (noting that the JADE Timor Passage values were obtained during an El Niño period)? Alternatively, might some of the Makassar transport pass back to the Pacific Ocean to the east of Sulawesi? Comparison of the MAK mooring results with: 1996-98 JADE mooring data near Timor (Molcard and Fieux); Lesser Sunda Island shallow pressure gauge array (Janet Sprintall); and data from the Arlindo mooring in Lifamatola Passage (Fig. 1) to be recovered in November 1998, may help resolve this issue.

The preliminary findings of the Arlindo of the 1998 CTD data supports the MAK measurements by clearly showing heaving of the thermocline in phase with ENSO. Additionally, the full Arlindo CTD set suggests that there may be a change in the ratio of North Pacific to South Pacific waters correlated with ENSO. The zonal CTD section across the Banda Sea reveals a large clock-wise gyre, which advects waters including excess freshwater from the Flores Sea to the northern Banda Sea, and then into the eastern Banda Sea southward flow. A clock-wise gyre was identified in earlier Arlindo CTD observations, but the gyre in 1998 encompassed the full Banda Sea. The Banda sea is the mixing pot for throughflow waters. The Makassar transport with the Java Sea export enters the Banda, as a river flows into a large lake. It mixes vertically and laterally with some salt addition from South Pacific thermocline, the blend passes southward in the eastern Banda Sea to enter the Timor passages and Indian Ocean. The

Banda Sea may be thought of as a buffer to the variability of input water from the Pacific Ocean, this may also apply to changing of the Makassar transport profile into a deeper reaching profile.

IMPACT/APPLICATIONS

The Makassar mass, heat and freshwater fluxes which will be obtained from the mooring data will have important effects on the varied models of the throughflow, which until now have been poorly constrained with *in situ* observations. At least in preliminary view, the seasonal and interannual variability of Makassar transport seems to be very different from that seen in models, or in the indirect or partial observation made within the Timor Sea. The Arlindo CTD and CFC data set with the mooring t-pod data will lead to a better understanding of the advective and mixing processes that shape the thermohaline stratification of the Indonesian Seas.

TRANSITIONS

The Arlindo products are of use to the development of regional and global ocean circulation models: Julie McClean (NPS), Vladimir Kamenkovich (USM), Roxana Wajsowicz (U Maryland) and Raghuram Murtugudde (NASA/GSFC) are all engaged in considering the impact of the Arlindo observations on models. There are also non-US transitions, mainly the joint analysis of the Arlindo and JADE (French-Indonesian) program, which measured Timor Sea transports at the time of the MAK moorings, and with Gary Meyers who is monitoring the thermal field from Java to Australia.

RELATED PROJECTS

The Arlindo Research is funded mainly by NSF, which also funds the Arlindo Indonesian research of Amy Ffield (temperature pods), Dale Pillsbury (current meters) of Oregon State University and Rana Fine (CFCs) of Rosenstiel School for Marine and Atmospheric Science. The Arlindo PIES research of Silvia Garzoli (LDEO) is funded by ONR. Remote sensing research is supported by NASA: Chet Koblinsky at the Goddard Space Flight Center. Janet Sprintall (Scripps Institution of Oceanography) has an array of shallow pressure sensors in the Lesser Sunda Islands, to monitor the time variability of the throughflow outflow in the Timor Sea as seen in the sea surface slope.

PUBLICATIONS

Gordon, A.L., S. Ma, D.B. Olson, P. Hacker, A. Ffield, L.D. Talley, D. Wilson, and M. Baringer (1997) Advection and Diffusion of Indonesian Throughflow within the Indian Ocean South Equatorial Current. *Geophys. Res. Lett.* 24(21): 2573-2576.

Gordon, A.L. and J. McClean (in press) Thermohaline Stratification of the Indonesian Seas-Model and Observations. JPO

A. Ffield and D. Pillsbury (submitted) Makassar Strait Transport: preliminary Arlindo Results from MAK-1 and MAK-2. *International WOCE Newsletter*.

Gordon, A. L. and R. Dwi Susanto, (submitted) Makassar Strait Transport: Initial Estimate Based on Arlindo Results. *Marine Science & Technology in the Asia-Pacific Region* Guest Editor Hassan Ali.

Top, Z., A. Gordon, P. Jean-Baptiste, M. Fieaux, A.G. Ilahude and M. Muchtar. 1997. ³He in Indonesian Seas: Inferences on Deep Pathways. *Geophys. Res. Newsletters*. 24(5): 547-550.